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OVERALL COEFFICIENT OF HEAT TRANSMISSION
OF HONEYCOMB STRUCTURE

A THESIS

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by

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Approved:

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SYMBOLS

A_C/A_T	Ratio of area transferring heat by conduction to area of metered heat flow.
A_G/A_T	Ratio of area transferring heat by radiation, or by a combination of gas conduction and free convection within the cell, to the area of metered heat flow.
A_M	Product of face sheet thickness and perimeter of metered area, ft^2
d	Distance from guard area thermocouples to edge of the metered area, ft
F_{1R}	Direct radiation factor
F_{1R2}	Total reradiation factor
F_e	Emissivity factor, $\varepsilon_1\varepsilon_2$
g	Acceleration of gravity, ft/sec^2
h	Heat transfer coefficient, Btu/hr-ft^2-°F
k_C	Thermal conductivity of core material, Btu/hr-ft-°F
k_F	Thermal conductivity of face sheet material, Btu/hr-ft-°F
k_G	Thermal conductivity of gas in cells, Btu/hr-ft-°F
k_i	Thermal conductivity of core material, Btu/hr-ft^2-°F/inch
ℓ	Thickness of test panel, ft
q	Rate of heat flow, Btu/hr
q_G	Rate of heat flow through gas in cells, Btu/hr
q_{GM}	Rate of heat flow from the guard area to the metered area, Btu/hr

T	Temperature, °F except as noted
T_{mean}	$(T_1 + T_2)/2$
T_{AB}	Average of temperatures measured by T/C's A and B, °F
T_{CD}	Average of temperature measured by T/C's C and D, °F
T_C	Temperature measured by T/C C, °F
T_F	Temperature measured by T/C F, °F
T/C	Thermocouple
ΔT	Difference between T_1 and T_2, °F
$\Delta T'$	Temperature difference between metered area and guard area, °F
U	Overall coefficient of heat transmission, Btu/hr-ft^2-°F
U_C	Coefficient of heat transmission by conduction through core material, Btu/hr-ft^2-°F
U_G	Coefficient of heat transmission through gas in the cells, Btu/hr-ft^2-°F
U_R	Coefficient of heat transmission by radiation, Btu/hr-ft^2-°F
Gr_ℓ	Grashof number, based on dimension ℓ
Nu_ℓ	Nusselt number, based on dimension ℓ
β	Coefficient of thermal expansion, 1/°R
δ_C	Core density, lb/ft^3
δ_M	Density of core material, lb/ft^3
ε	Total normal emissivity
ν	Kinematic viscosity, ft^2/hr

σ Stefan - Boltzmann Constant = 0.173 x 10^{-8} Btu/hr-ft^2-°R^4

τ Foil thickness, inches

Φ Function of

SUBSCRIPTS

1 Hot side of panel

2 Cold side of panel

SUMMARY

Steady - state heat flow through honeycomb structures is investigated analytically and compared with experimental data obtained during this study and from another source. The results are presented as a comparison of the analytically-determined and the measured values of the overall coefficient of heat transmission.

For the analytical investigation, it was assumed that the various heat paths were independent of one another. The heat paths considered were (1) conduction through the core material, (2) combination of gas conduction and convection within the cells, and (3) radiation and reradiation from the hot side of the panel to the cold side.

The experimental program involved several panels which provided various combinations of cell sizes, foil thicknesses, brazing materials, and temperatures; however, the correlation with analytical work was done only with the test runs that provided data that were more predictable in that control of certain conditions was maintained during fabrication. These conditions include node flow, defined as the undesirable heat path provided by the flow of brazing material from one face sheet to the other.

CHAPTER I

INTRODUCTION

For a number of years, aircraft performance was limted by powerplant capabilities and aerodynamic considerations. Advancements in these fields, however, have brought about the advent of aircraft which are capable of flying at such high speeds that the effect of aerodynamic heating becomes a significant factor. This is known as ram air temperature rise and it can be shown that the skin temperature, even though tempered by the fact that air dissociates at high temperature, can rise to intolerable levels at high Mach numbers. This is shown in graphical form on page 31.

Materials have been developed which are capable of withstanding high temperatures; however, from the standpoint of the strength-weight ratio, no one single material has been developed that will maintain sufficient strength at these high temperatures and still allow adequate aircraft performance.

This situation presents the problems of incorporating into the aircraft design a means of combating aerodynamic heating. Several means have been proposed for handling this problem; however, they usually involve the dissipating of rather than the retarding of heat flowing into the structure. These include:

1) Transpiration cooling, i.e., evaporative cooling by forcing a liquid or gas through the skin into the boundary layer.

2) Use of fuel as a heat sink.

3) Use of a mechanical refrigeration system.

4) Internal storage of a solid cooling material, such as ice or solid carbon dioxide.

All of the above methods of dissipating heat will work, but they have certain disadvantages. For example, transpiration cooling imposes a weight penalty in that the liquid is excess baggage and contributes nothing to the aircraft performance. Use of the fuel in forced convection or as a heat sink has been used before but several of the modern fuels break down at elevated temperatures and also, it is conceivable that the fuel will not be liquid. A mechanical refrigeration system and the use of a cooling material have the disadvantage of imposing weight penalties.

For some time, a considerable amount of effort has been expended in the search for better materials for high-speed flight. The most common structural material used in aircraft to date has been aluminum alloy. It can be seen from the ram air temperature curve (page 31) however, that the useful range for aluminum-alloy structure cannot be pushed much beyond Mach 2. Titanium, long considered a material which would solve this particular problem, is satisfactory only to about Mach 3. The high-nickel steels extend the range only a little farther. At this stage, even though development of materials continued, interest picked up in the field of specialized structural configurations. One of these, honeycomb, has been developed to the extent where it is used in large quantities on some of the most modern aircraft.

The honeycomb structure is composed of a honeycomb core sandwiched between two plates and bonded by a suitable bonding agent. A large variety of materials are fabricated into honeycomb structure: for low and medium temperature aluminum alloys and plastics are used, whereas, at higher temperatures heat resisting materials such as stainless steel are employed. The core is available in many different cell design, such as square, sine wave, hexagonal, etc., and dimensions vary over a wide range.

To perform its assigned function, the structure must be able to resist the flow of heat and yet maintain structural integrity. The prediction of apparent thermal conductivity of honeycomb structure presents certain problems, but it will be shown that this can be done with a reasonable degree of accuracy. In addition, this investigation pointed out several areas that promise further refinements in the ability of honeycomb structure to resist the flow of heat.

CHAPTER II

EXPERIMENTAL RESULTS

The experimental tests were conducted with a guarded hot box constructed to handle the particular specimens used in the experimental program. A schematic drawing of the test apparatus is shown on page 30.

Basically, the apparatus consisted of an insulated chamber on which was placed, in a horizontal position, the test panel. The test panel in all cases was 18" x 18" in size, but the guarded hot box itself had the nominal dimensions of 6" x 6". The guarded hot box was placed underneath and in physical contact with the test panel. Basic heat flow through the test panel was supplied by direct current resistance heaters placed within the hot box and was measured by means of a voltmeter and an ammeter in the power lines.

The heaters immediately downstream of the circulation fans were supplied with 220V power through two variable-voltage transformers, one of which was maintained at constant power input and the other was controlled to vary the power input. The same voltage (controlled) was supplied to nichrome wire on the outside of the hot box, the purpose being to maintain, as closely as possible, zero heat flow through the insulation.

Iron-constantan thermocouples, imbedded in the insulation or spotwelded to the test panel, were used throughout. The leadwires were taped to the surfaces to which the thermocouples were attached and brought out of the test apparatus to a point where they could be connected to a Minneapolis-Honeywell 16-channel strip chart recorder, Type 153X, which had an accuracy of $\pm 2°F$. Temperature readings from four thermocouples were averaged to obtain the panel hot side temperature, three were averaged to obtain the cold side temperature, and four were averaged to obtain the guard temperature. Temperatures for monitoring heat flow through the insulation were also recorded. Locations of thermocouples utilized in this program are shown on pages 28 and 29.

It would appear that the only data necessary to calculate the overall coefficient of heat transmission through the panel are the power supplied to the heater in the guarded hot box, the area of the heat path through the panel, and the temperature difference across the panel. However, difficulties were experienced in maintaining guard temperatures equal to the panel hot side temperature and in maintaining zero heat flow through the insulation of the hot box. Rather than spend an inordinate amount of time doing this, it was decided to approach the ideal experimental conditions as closely as possible and correct the indicated heat flow rate by these stray gains or losses.

Correction for Heat Flow Along Face Sheet.--This correction involved heat flow between the guard and the metered area and is based on the assumptions that (1) all heat flow through the metered hot side face sheet is normal to the panel and (2) temperature varies linearly between the guard area thermocouples and the edge of the metered area in the calculations of heat flow parallel to the panel hot side surface.

Representing this heat flow between the guard and metered areas as q_{GM}, the following expression was used in calculating the correction applied to the experimental data:

$$q_{GM} = \frac{k_F \; A_M \Delta T'}{d}$$

where k_F = thermal conductivity of face sheet material

d = 1 inch (distance from guard area thermocouples to metered area boundary).

A_M = (Face sheet thickness)(metered area perimeter)

$\Delta T'$ = Temperature difference between metered and guard area

This correction was applied to all of the experimental data. Care was taken during testing however, so that this effect was negligible in most cases.

<u>Correction for Heat Flow through Insulation of Hot Box.</u>--This correction involved heat flow to or from the insulated guarded hot box. In order to apply this correction, temperatures were measured on the inside and the outside of the hot box and the following expressions were applied:

Heat loss (or gain) through bottom of the 1" thick hot box =

$$k_i \times \frac{49}{144} (T_{DE} - T_{AB})$$

Heat loss (or gain) through sides of the 1" thick hot box =

$$k_i \times \frac{36}{144} (T_F - T_C)$$

<u>Calculation of Overall Coefficient of Heat Transmission.</u>--Heat flow supplied to the hot box in the form of electrical power was calculated from

$$q_{unc} = \text{Volts} \times \text{Amps} \times 3.41$$

Corrections to q_{unc}, as discussed above, allows calculation of a corrected heat flow value,

$$q_{corr} = q_{unc} \pm (\text{heat flow to or from guarded area})$$
$$\pm (\text{heat flow through insulation of hot box})$$

From this, the overall coefficient of heat transmission through the panel may be calculated.

$$U = \frac{q_{corr}}{A\Delta T}$$

where ΔT is the difference between the hot side temperature (average of T/C's 1, 2, 3, 4) and the cold side temperature (average of T/C's 10, 13, 14), and

where A is based on the effective area of the opening of the hot box through which heat flows into the panel. Assuming that this area includes half of the 3/8" silicone rubber lip which provides firm contact with the panel, the area in the above equation is 0.282 ft^2.

Data representing experimentally-determined values of U are plotted as a function of mean temperature on pages 36 and 37.

CHAPTER III

ANALYTICAL RESULTS

Inasmuch as the structure under consideration contains gas cells within the core, heat flow will occur by conduction in the core material, by conduction and convection in the gas within the cells, by radiation from the hot to the cold surface, and by conduction along the nodes. An analytic investigation of the latter phenomena will not be attempted; however it will be considered during the discussion wherein experimental and calculated results will be correlated.

The following basic assuptions were made in this analysis:

1) The face sheets offer zero resistance to heat flow. This is a reasonable assumption in view of the relatively high thermal conductivity and the thickness of the face sheet material compared to the core.
2) Conduction through the metal core, radiation and reradiation between metallic parts, and conduction and convection of the gas within the cell are considered independent of one another.
3) Melting of the brazing material does not increase the thickness of the face panel or change the emissivities of radiating surfaces.

By operating with overall coefficients of heat transmission, the procedure for investigating heat flow through honeycomb may be somewhat systematized. The overall coefficient of total heat transmission is shown to be

$$U = U_C + U_G + U_R$$

where the various U's can be expressed as

$$U_C = \frac{k_C}{\ell} \frac{A_C}{A_T}$$

$$U_G = \frac{k'_G}{\ell} \frac{A_G}{A_T}$$

$$U_R = F_{1R2}\ \sigma F_e \frac{(T_1^{\ 4} - T_2^{\ 4})}{(T_1 - T_2)} \quad \frac{A_G}{A_T}$$

At this point, several matters will be clarified. One of these, the terms A_C/A_T and A_G/A_T introduced above, represent the ratio of the area transferring heat to the total plate area. Another matter is the element of heat flow through the nodes caused by flow of brazing material from one face to the other. Evaluation of this phenomena is difficult, but it will be discussed.

Coefficient of Heat Transmission by Conduction through Core Material.-- Pertinent equation relating to this factor are

$$q_C = U_C A_T (T_1 - T_2)$$

and

$$q_C = \frac{k_C A_C (T_1 - T_2)}{\ell}$$

Equating these two expressions gives

$$U_C = \frac{k_C}{\ell} \frac{A_C}{A_T}$$

Pages 32 and 33 present the variation of thermal conductance of the material used in experimental work.

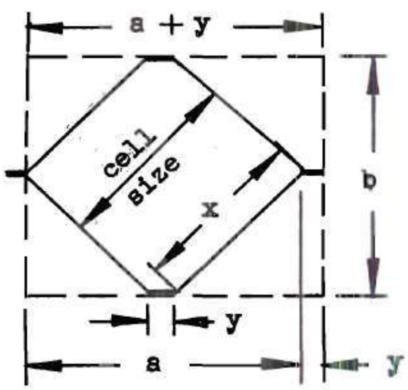
A_C/A_T may be determined in two ways:

1) Dividing the core density by density of core material:

Since $A_T \ell \delta_C = A_C \ell \delta_M$

$$\frac{A_C}{A_T} = \frac{\delta_C}{\delta_M}$$

2) From geometrical data:



y = core node width

$(a + y)$ = longitudinal pitch

b = transverse pitch

$y = a - b$

$$x = \frac{(a - y)\sqrt{2}}{2} = \frac{b}{\sqrt{2}}$$

$$A_C = (4x + 4y)\tau = 4\left(\frac{b}{\sqrt{2}} + a - b\right)\tau$$

Since <u>a</u> usually is not given in specifications, it will be necessary to express it in terms of dimensions that are known.

$$y + (y) = a - b + (y) = (a + y) - b = \text{long. pitch} - \text{trans. pitch}$$

$$y = \frac{(a + y) - b}{2}$$

Hence $a = y + b = \frac{(a + y) - b}{2}$

$$A_C = 4\left(\frac{b}{\sqrt{2}} + \frac{[a + y] + b}{2} - b\right)\tau = 4\left(\frac{\sqrt{2}\,b + [a + y] + b - 2b}{2}\right)\tau$$

$$= 2[(a + y) + 0.414b]\tau$$

and

$$A_C/A_T = \frac{2[(a + y) + 0.414b]\tau}{(a + y)b}$$

Hence,

$$U_C = \frac{k_C}{\ell}\,\frac{2[(a + y) + 0.414b]\tau}{(a + y)b}$$

The table on page 26 shows the calculated variation of U_C with mean temperatures for the configuration analytically investigated.

Coefficient of Heat Transmission through Gas in the Cells.--

Jakob, (Ref. 2), indicates that heat transmission by free convection in horizontal and vertical gas layers has been investigated by several people but most elaborately by Mull and Reiher. As one factor contributing to heat exchange in a gas layer they used an equivalent thermal conductivity which includes the effect of gas conduction and free convection within the layer.

The rate of heat flow through a gas layer between two surfaces which are at different temperatures can be expressed by

$$q_G = \frac{k_G\, A_G(T_1 - T_2)}{\ell}$$

where k_G' is the equivalent thermal conductivity.

Jakob further shows, by dimensional analysis, that

$$Nu_\ell = \Phi(Gr_\ell)$$

where

$$Nu_\ell = \frac{h\ell}{k_G} = \frac{q_G}{A_G(T_1 - T_2)} \frac{\ell}{k_G} = \frac{k_G'}{k_G}$$

and

$$Gr_\ell = \frac{\beta g}{\nu^2} \ell^3 (T_1 - T_2)$$

Experimental results by Mull and Reiher were correlated by Jakob and, for a diatomic gas enclosed between horizontal parallel plates with heat flow upward and separated by strips of wood to form various rectangular grids, were found to agree very closely with the equations

$$\frac{k_G'}{k_G} = 0.068(Gr_\ell)^{\frac{1}{3}} \text{. For } Gr_\ell \overline{>} 400{,}000$$

and

$$\frac{k_G'}{k_G} = 0.195(Gr_\ell)^{\frac{1}{4}} \quad \text{for } 10{,}000 < Gr_\ell < 400{,}000$$

Note that the Mull and Reiher experiments showed that when the plates are mounted horizontally with heat flow upward, k_G'/k_G is independent of any dimension other than the distance between the two plates. This method of mounting was utilized for the experimental program conducted for this thesis.

On the basis of the above, an overall thermal conductivity, including the effect of gas conduction and convection within the cells, may be expressed as

$$U_G = \frac{k_G}{\ell} \frac{k_G'}{k_G} \frac{A_G}{A_T}$$

$$U_G = \frac{k_G}{\ell} \frac{k_G'}{k_G} \left(1 - \frac{A_C}{A_T}\right)$$

<u>Coefficient of Heat Transmission by Radiation</u>.--Heat transmission by radiation from one surface to another is usually expressed as

$$q = F_{1R}\ \sigma\ A_G(T_1^{\ 4} - T_2^4)$$

However, in the presence of reradiating walls,the net radiant heat transfer is represented by

$$q_{net} = F_{1R2}\ \sigma\ A_G F_e (T_1^{\ 4} - T_2^{\ 4})$$

Determination of the factor F_{1R2} is rather involved and requires the solution of integral equations. Hottel and Keller have done this and have plotted the results as a function of ratio of diameter (or least width) to the thickness of the wall. In this particular case, it would be the ratio of cell size to height of core material. Since the configuration of the honeycomb core considered herein is somewhat hexagonal, the Hottel and Keller curves for a square opening and a round opening will be averaged. This is a reasonable approach since, as shown on page 35, there is very little difference between this factor for the two configurations. The term F_e is a factor which allows for the departure of the two primary radiating surfaces from a black body and, from Ref. 1, is numerically equal to $\varepsilon_1 \varepsilon_2$ when the surfaces are connected by reradiating and non-conducting walls. The condition of non-conducting walls is not met, but this is still a reasonable assumption since radiation is a small contribution. The total normal emissivity of 17-7PH stainless steel was obtained from the extensive program reported in Ref. 7 and, depending upon the surface condition, varies between 0.05 and 0.15 between temperatures of 500°F and 1500°F.

From the standpoint of overall heat transmission by radiation,

$$q_R = U_R A_T (T_1 - T_2)$$

Comparing this with the other expression for heat transmission by radiation, we obtain the following:

$$U_R = \frac{F_{1R2} \sigma F_e (T_1^{\,4} - T_2^{\,4})}{(T_1 - T_2)} \frac{A_G}{A_T}$$

Heat Coefficient of Heat Transmission.--Summing up, the total overall coefficient of heat transmission may be represented as

$$U = U_C + U_G + U_R$$

where

$$U_C = \frac{k_C}{\ell} \frac{A_C}{A_T}$$

$$U_G = \frac{k_G}{\ell} \frac{k'_G}{k_G} \frac{A_G}{A_T}$$

and

$$U_R = \frac{F_{1R2}\ \sigma\ F_e(T_1^{\ 4} - T_2^{\ 4})}{(T_1 - T_2)} \frac{A_G}{A_T}$$

CHAPTER IV

CORRELATION OF EXPERIMENTAL AND ANALYTICAL DATA

The experimental data includes runs made with various sizes of honeycomb at various mean temperatures and temperature differences. The data are plotted on page 36 and show a considerable variation which can be attributed to node flow. Node flow is the phenomenon that occurs when the brazing material flows, because of excessive brazing temperatures, from one face sheet to the other. Since the material is composed primarily of silver, this provides a very good heat path. X-ray techniques were used to define the extent to which this condition exists. This technique was employed after each panel was fabricated and was found to be very useful in observing certain conditions upon which following tests, thermal and structural, were dependent. The photographs permitted an experienced observer to establish the degree to which node flow occurred and to determine whether the core material had collapsed or been crushed during fabrication.

During the latter phases of the development program at Lockheed, the technique for fabricating this type of structure was considerably improved with the result that several panels were made which had no node flow. These eleven test runs, plotted on page 37, form the basis for correlation with analytical results. Plotted also on page 37 are data which give an indication of the relative degree of severity of this effect on the overall coefficient of heat transmission of honeycomb structure.

All of the experimental data utilized in the correlation were obtained from the panels whose core had a cell size of 1/4 inch and was made of foil 0.0015 inches thick. The faces sheets varied slightly in thickness, but it can readily be shown that they offer very little resistance to heat flow. The data plotted for correlation purposes had, with the exception of previously mentioned data, zero node flow. The exception was included to show the relative magnitude of the effect of node flow.

In the analytical determination of overall coefficient of total heat transmission, mean temperatures and ΔT's encompassing those obtained in the experimental work were assumed. It was found, however, that assuming a ΔT of 200°F gave values of U that varied only $\pm$ 5 percent from those obtained when assuming ΔT's of 100°F and 300°F. This is true only for the range of temperatures investigated. At higher temperatures, the variation will be greater, primarily because of the effect of the fourth power of absolute temperature in the radiation term.

Evaluating the relative magnitude of factors contributing to heat transmission, it is obvious that conductivity has the greatest effect on flow of heat from one face sheet to the other. There is nothing that can be done about this since other requirements usually dictate the material to be used.

The next most important contribution to heat transmission is that afforded by the combination of conduction and convection of the gas contained within the cells. The fabrication of the panels requires that the brazing be performed in an argon atmosphere, therefore the panels, before brazing, are purged with argon and evacuated to a very low pressure in order that good contact is made between all the surfaces to be bonded. The greatest resistance to heat transmission would exist when the cells maintained the condition of being filled with argon at about 0.01 atmospheres. However, examination of some test specimens revealed cases in which tiny imperfections in joining the core material itself allowed air to bleed into the cells. For this reason, and since this assumption provided the most conservative results, the cells were assumed to be filled with air at one atmosphere. This assumption appears to be realistic on the basis of the correlation.

The heat transmission attributed to radiation from the hot panel to the cold panel and the reradiation from the walls of the cell was shown to have the least bearing on total heat transmission. This will vary with cell size, but for the size selected for correlation, its effect is very small. Inspection of page 35 shows how the variation of cell size or core thickness will change the total reradiation factor, F_{1R2}.

As shown on page 37, an excellent correlation was obtained between the experimental and analytical results unique with this thesis. Other experimental data (Ref. 8) did not correlate as well even though the panel was made of the same material and, from the information given, was of the same material, cell size, and foil thickness. The predominant unknown is that of the adhesive used in bonding the face sheets to the core. It was of a different type and there is no way of determining its effectiveness in transferring heat; however, inspection of the experimental data, page 37, supports the argument that node flow was a factor in those tests.

CHAPTER V

DISCUSSION

During both the analytical and the experimental portions of this investigation, several assumptions were made which have an important bearing on the results obtained. In an attempt to evaluate the effect of these assumptions and to point out further refinements which could be made to combat the basic problems that precipitated this endeavor, i.e., the thermal problems associated with high speed flight, further discussion of factors contributing to the overall coefficient of total heat transmission is in order.

In the analytical investigation of heat transmission by conduction and convection of the gas in the cells, U_G, it was assumed that the gas consisted of air at one atmosphere pressure and indeed, examination of some samples and the correlation seems to establish this as a fact. Since this term alone constitutes approximately 35 percent of the total U, it can be shown that a sizable improvement can be made if better control can be exerted over this factor. For example, if it were possible to maintain the gas within the cells at the same conditions as when the brazing was performed, i.e., argon at 0.01 atmosphere, U_G would reduce to almost zero. If, from a fabrication standpoint, this is not feasible, then an experimental investigation with the air in the cells displaced by a light filler material appears to be worthwhile. This technique would also eliminate heat transfer by radiation. Even though this contribution is negligible for the example considered, it would be an important consideration under certain conditions encountered in flight with hypersonic vehicles.

For direct application of this investigation to a flying vehicle, allowance should be provided for the fact that heat transmission by conduction and convection of the gas in the cells is a function of the Grashof number which, in turn, is a function of the acceleration of gravity, g. Inspection of this factor shows that the transition from 1g level flight to a 3g maneuver will triple Gr_{ℓ}. This is a sizable increase and certainly warrants further investigation. A further increase will occur to U_G if the cell size is increased while maintaining the same core foil thickness.

In the equation used for the analytical determination U_G, it was assumed that the panel was mounted horizontally with heat flow upward. Since there certainly will be some areas of a vehicle in which honeycomb structure will be oriented differently, e.g., the side of the fuselage or the vertical tail surfaces, it is interesting to note the difference in U_G caused by mounting the panel vertically instead of horizontally. Mull and Reiher experimentally showed that when the surfaces were mounted horizontally, k'_G/k_G is independent of any dimension other than the thickness of the panel. However, when the surfaces were mounted vertically the conditions are less simple in that k'_G/k_G is not independent of the height of the layers, in this case the cell size. A numerical example will serve to illustrate the difference. For the horizontal position

$$k'_G/k_G = 0.195\ (Gr_{\ell})^{\frac{1}{4}} = 3.41$$

Rotating the panel to a vertical position and maintaining other conditions the same as for the calculations above, this term, for a 1/4" cell size honeycomb structure, becomes

$$k_G'/k_G = 0.18(Gr_{\ell})^{\frac{1}{4}} (H/\ell)^{-\frac{1}{9}} = 3.97$$

Where H is the height of the cell when the panel is in the vertical position.

This factor, $(H/\ell)^{-\frac{1}{9}}$, is certainly not valid down to $H/\ell = 0$ since this would yield an infinitely large heat transfer. By the same token, for the dimensions usually used with honeycomb structures, its influence is relatively minor. It is interesting to note that Mull and Reiher, on the basis of results obtained from a test panel inclined at a 45° angle, indicate that linear interpolation between the formulas for horizontal and vertical panels is directly related to the angle of inclination.

The contribution of heat transmission by radiation is negigible for the example considered in the correlation. Considering only the configuration utilized, it can be shown that U_R will be doubled merely by increasing the cell size from 1/4" to 1/2".

Throughout this investigation, heat flow by gas conduction and convection was based on the assumption that it flowed upward. Of equal importance in actual application is the case in which heat flow is downward. Even though no attempt has been made to evaluate this condition, it is obvious that heat transmission would be less.

TABLE I

CALCULATION OF A_C/A_T AND COMPARISON WITH SPECIFICATIONS

Size	a + y	b	A_C/A_T	Specification Min.	Specification Max.
3/16 - 0.0010	0.295	0.240	0.0100	0.0101	0.0130
3/16 - 0.0015	0.295	0.240	0.0150	0.0153	0.0195
3/16 - 0.0020	0.295	0.240	0.0199	0.0206	0.0260
1/4 - 0.0010	0.390	0.320	0.0084	0.0078	0.0099
1/4 - 0.0015	0.390	0.320	0.0126	0.0115	0.0147

TABLE II

TYPICAL REQUIREMENTS FOR CORE MATERIAL

Cell Size-Foil Gage Inches	Core Density: Lb/Cu. Ft. Typical	Max.	Min.	Cell Pitch: Inches Trans.	Long.
3/16 - 0.001	5.5	6.2	4.8	0.240	0.295
3/16 - 0.0015	8.3	9.3	7.3	0.240	0.295
3/16 - 0.002	11.1	12.4	9.8	0.240	0.295
1/4 - 0.001	4.2	4.7	3.7	0.320	0.390
1/4 - 0.0015	6.2	7.0	5.5	0.320	0.390

DENSITY OF CORE MATERIAL - 477 Lb/Cu. Ft.

REF: ARMCO Technical Data Manual, Feb. 15, 1954

TABLE III

SUMMARY OF EXPERIMENTAL DATA

Panel	Cell Size	Foil Thickness	Panel and Face Sheet Thickness	Node Flow (1)	Fillets Top	Fillets Bottom	T_{MEAN}	ΔT	U
1	3/16"	0.0015	1"x0.040"	100%	Light	Light	384°F	84°F	6.66
							286	273	6.20
							193	90	5.70
							206	105	5.80
2	3/16"	0.002	1 x 0.024	100%	Light	Light	297	74	5.07
							284	281	5.16
							287	281	5.18
							284	280	5.13
							167	132	4.80
3	3/16"	0.002	1 x 0.025	30%	Light	Light	290	296	4.24
							201	183	3.75
4	1/4"	0.0015	1 x 0.040	(2)	Light	Med.	193	177	3.13
							281	294	3.49
							288	292	3.58
5	1/4"	0.0010	1 x 0.040	100%	Light	Med.	262	272	3.59
							287	300	3.75
							225	159	3.44
6	1/4"	0.0015	1 x 0.052	None	Light	Med.	267	287	2.41
							262	56	2.25
							254	52	2.28
							242	48	2.29
7	1/4"	0.0015	1 x 0.040	None	Light	Med.	301	309	2.22
							283	63	2.11
							293	66	2.13
							292	309	2.16
							292	310	2.20
8	1/4"	0.0015	1 x 0.040	None	Light	Heavy	299	307	2.37
							306	308	2.33
9	3/16"	0.0010	1 x 0.090	None	Light	Light	311	70	2.41
							297	294	2.39

(1) A value of 100% indicates that full nodes formed at every intersection of the core foil.

(2) 10% full nodes, 90% partial nodes

TABLE IV

SUMMARY OF ANALYTICAL DATA

Cell Size: 1/4"- 0.0015"

T_{MEAN}	T	U_C	U_G	U_R	U
160	200	1.36	0.75	0	2.11
200	200	1.39	0.74	0.01	2.14
240	200	1.42	0.73	0.01	2.16
280	200	1.44	0.72	0.01	2.17
320	200	1.47	0.71	0.01	2.19

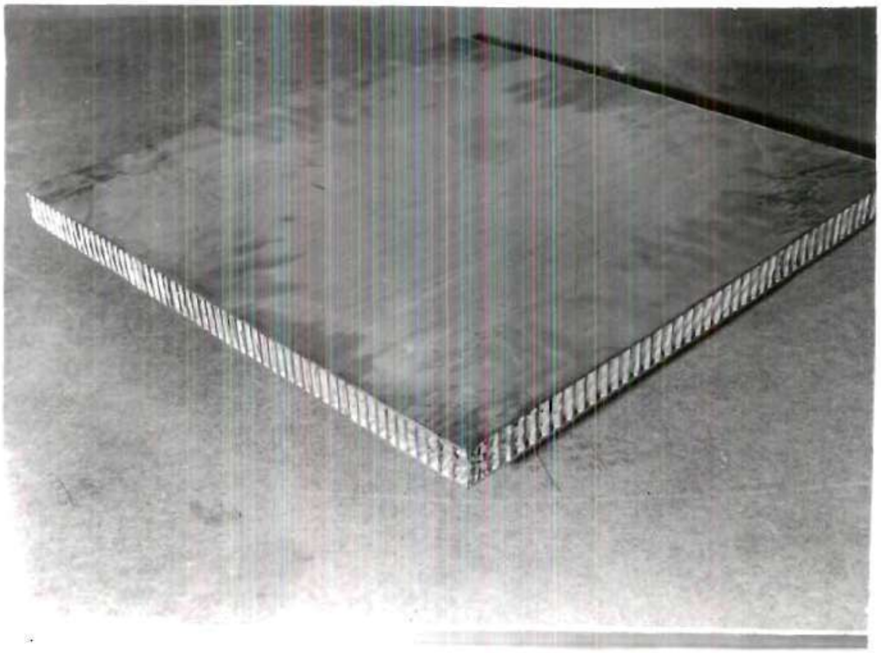


Figure 1. Typical Test Specimen

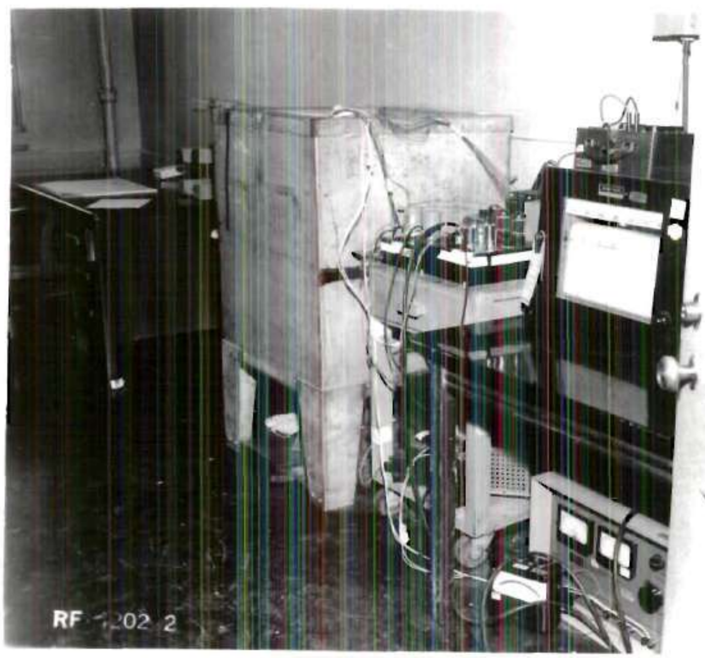


Figure 2. Photograph of Test Equipment

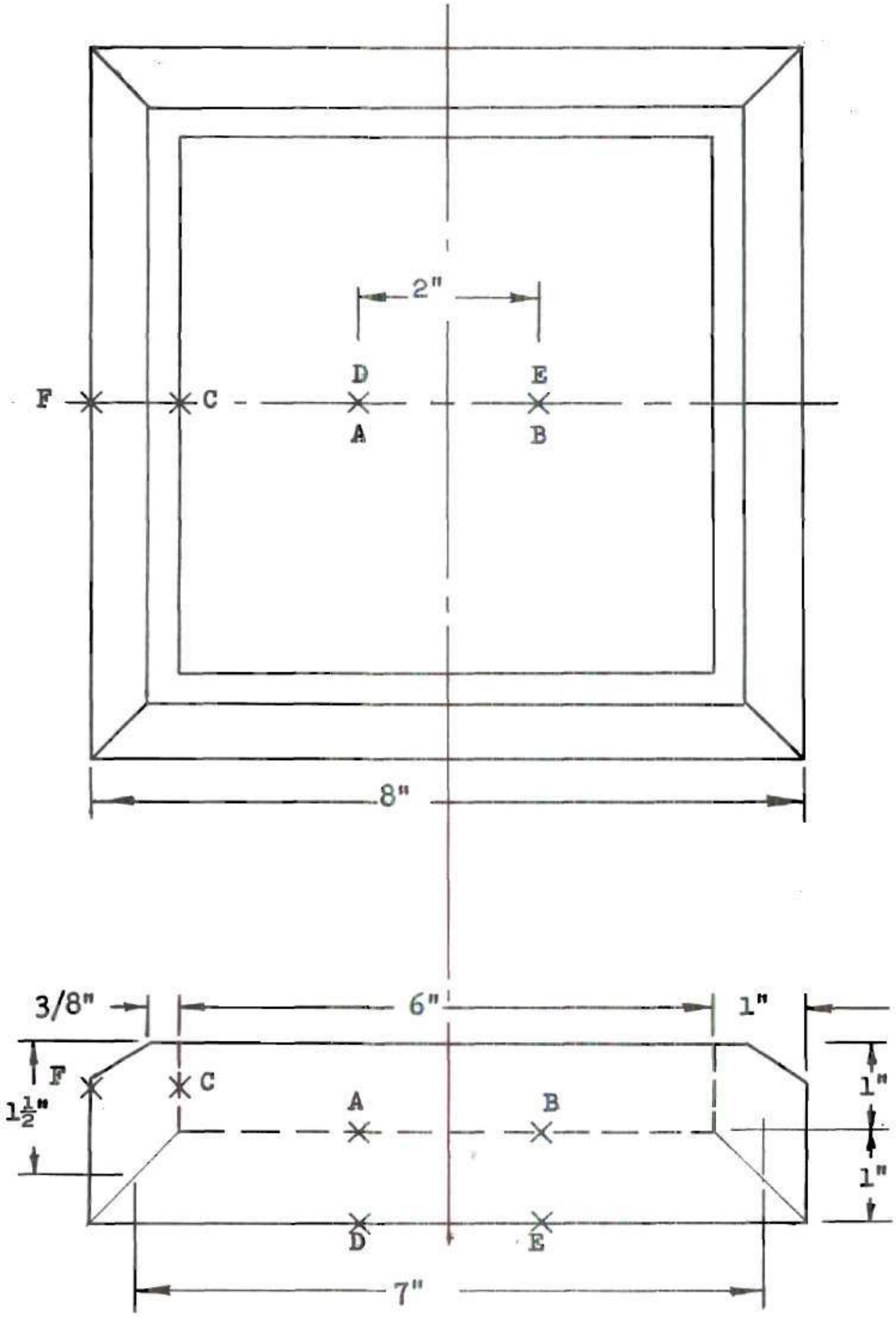
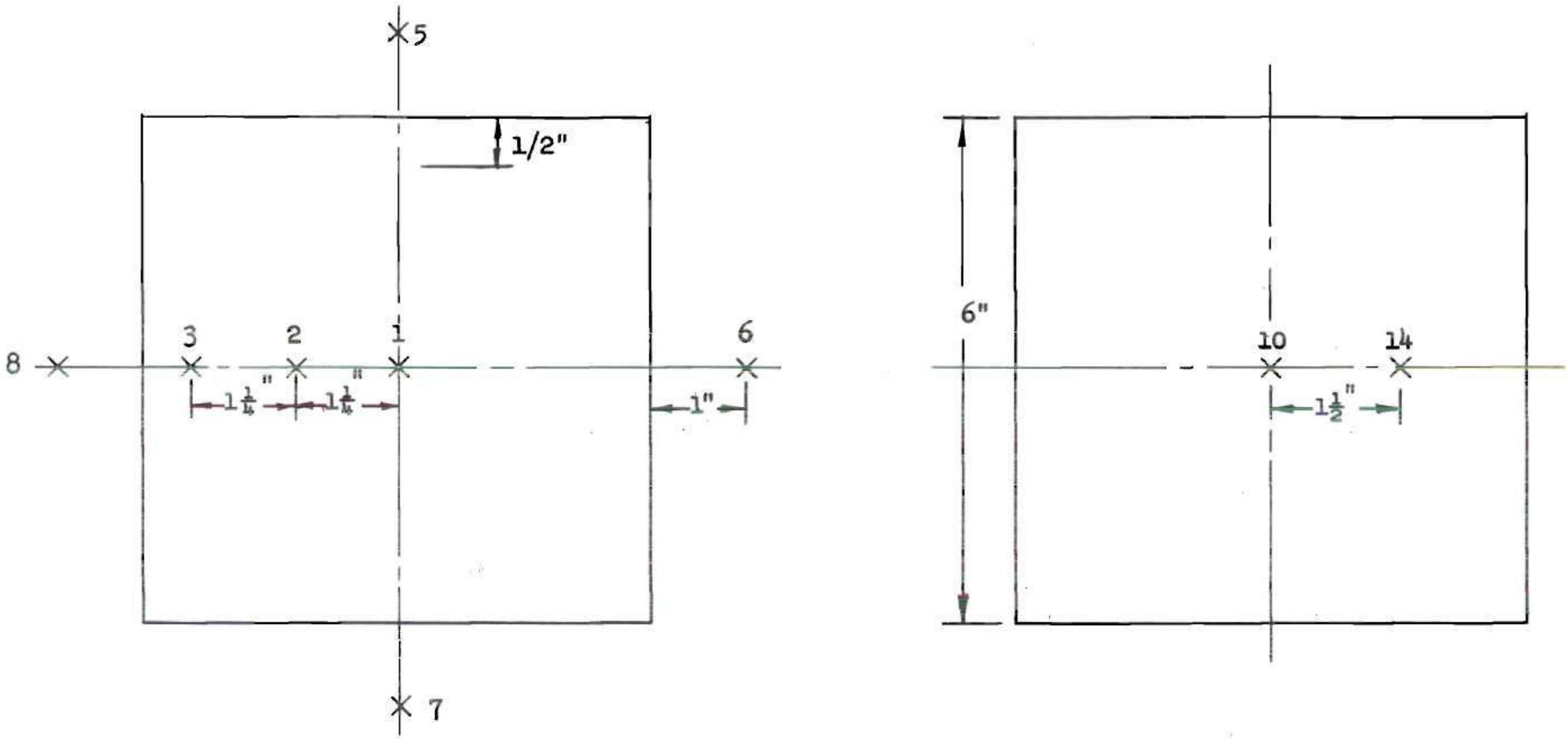


Figure 3. Location of Thermocouples for Measuring
Heat Flow Through Insulation of Hot Box



Looking at Hot Side

Looking at Cold Side

Figure 4. Location of Thermocouples for Measuring Heat Flow Through Panel and Between Guard and Metered Areas.

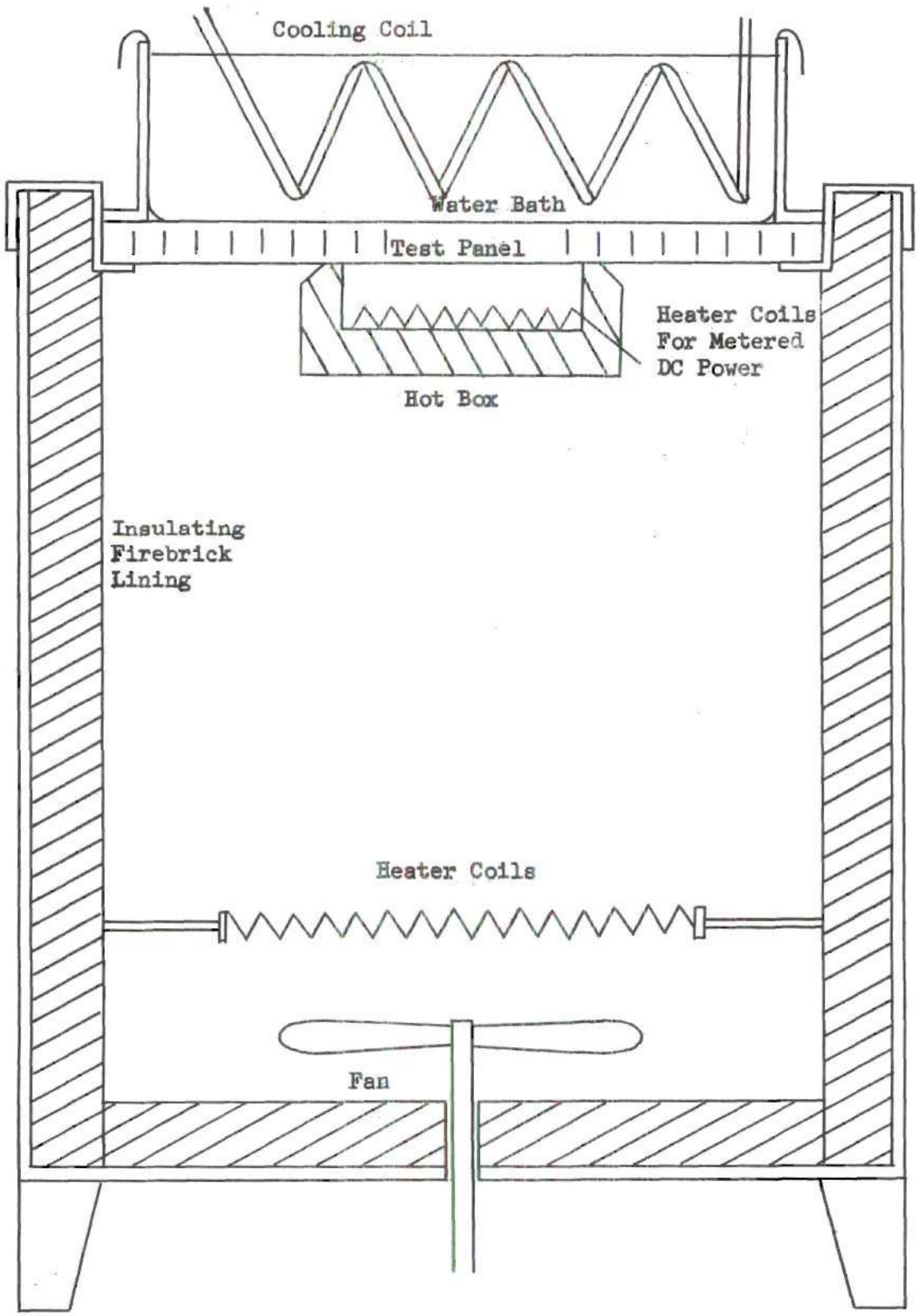


Figure 5. Schematic of Test Apparatus

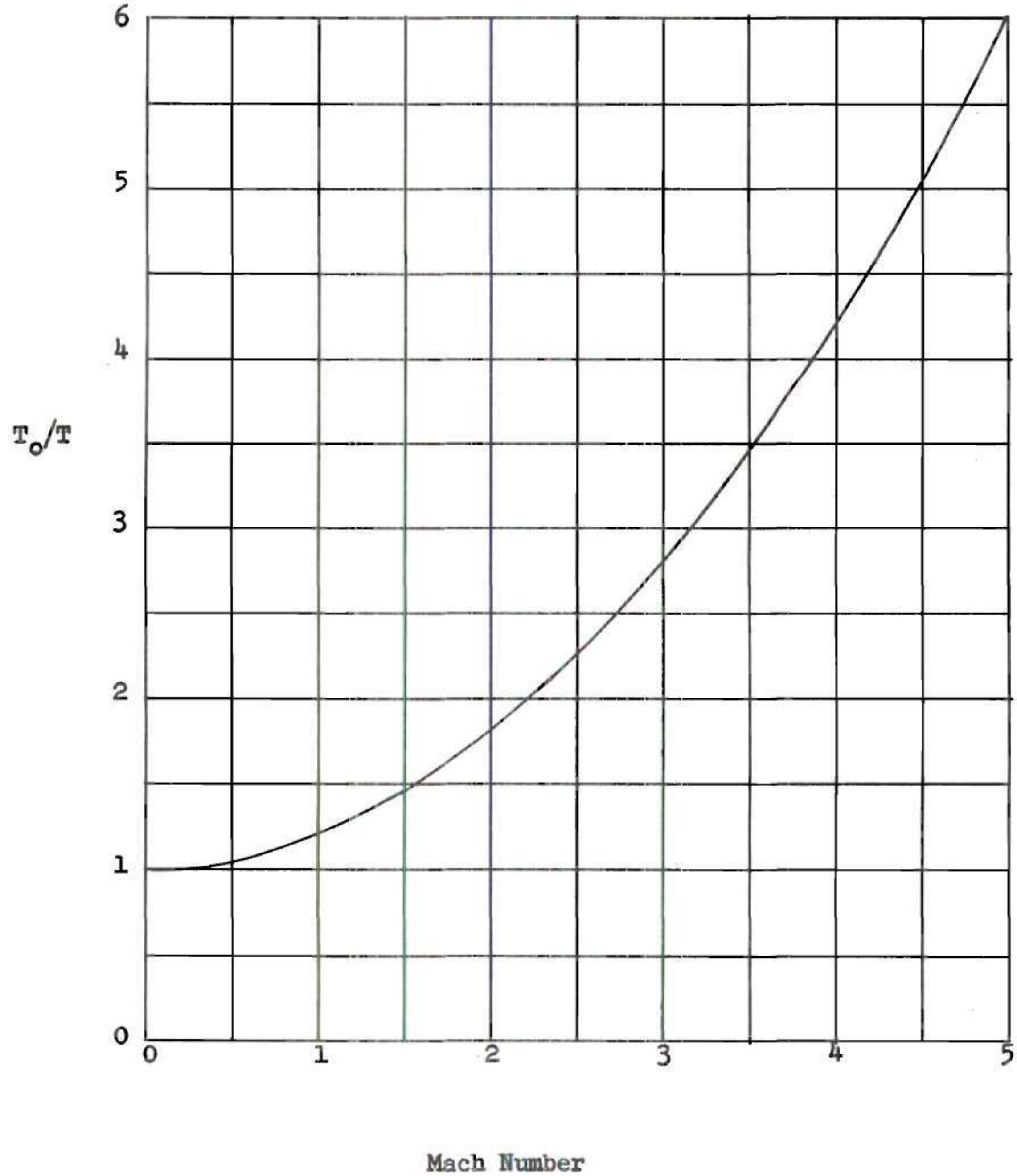


Figure 6. Variation of T_o/T with Mach Number

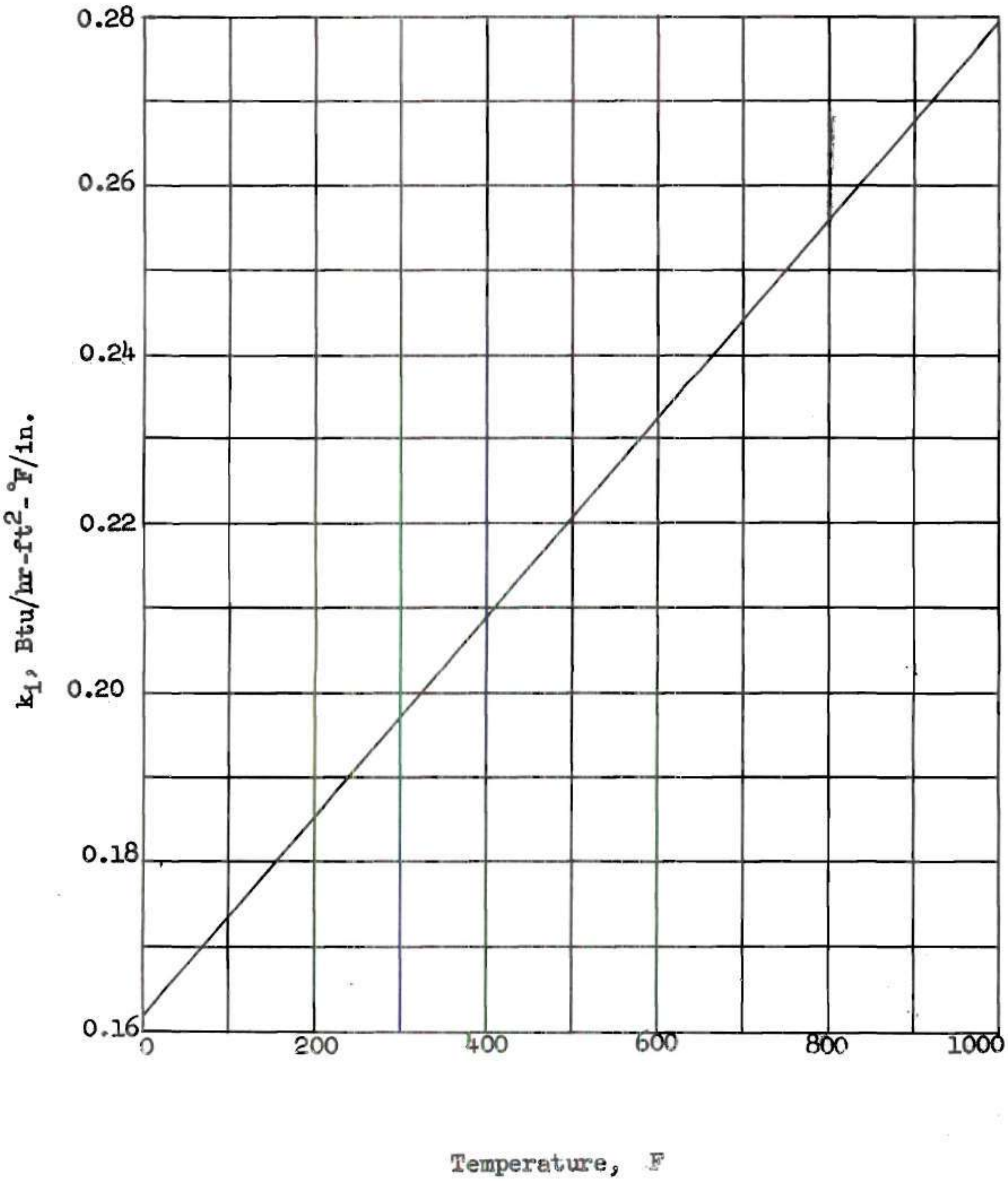


Figure 7. Thermal Conductivity of Johns-Manville MIN-K

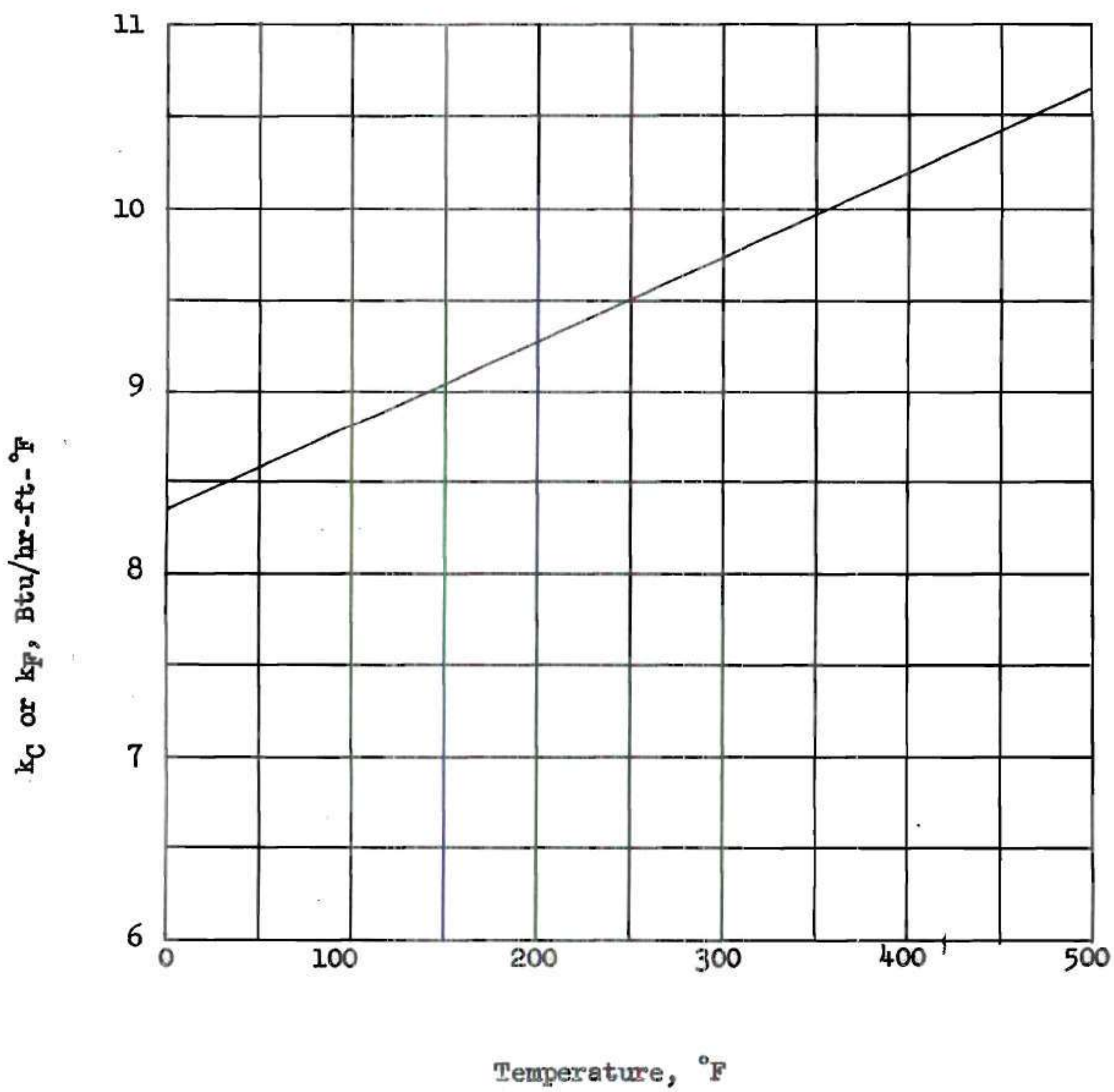


Figure 8. Thermal Conductivity of 17-7PH Stainless Steel

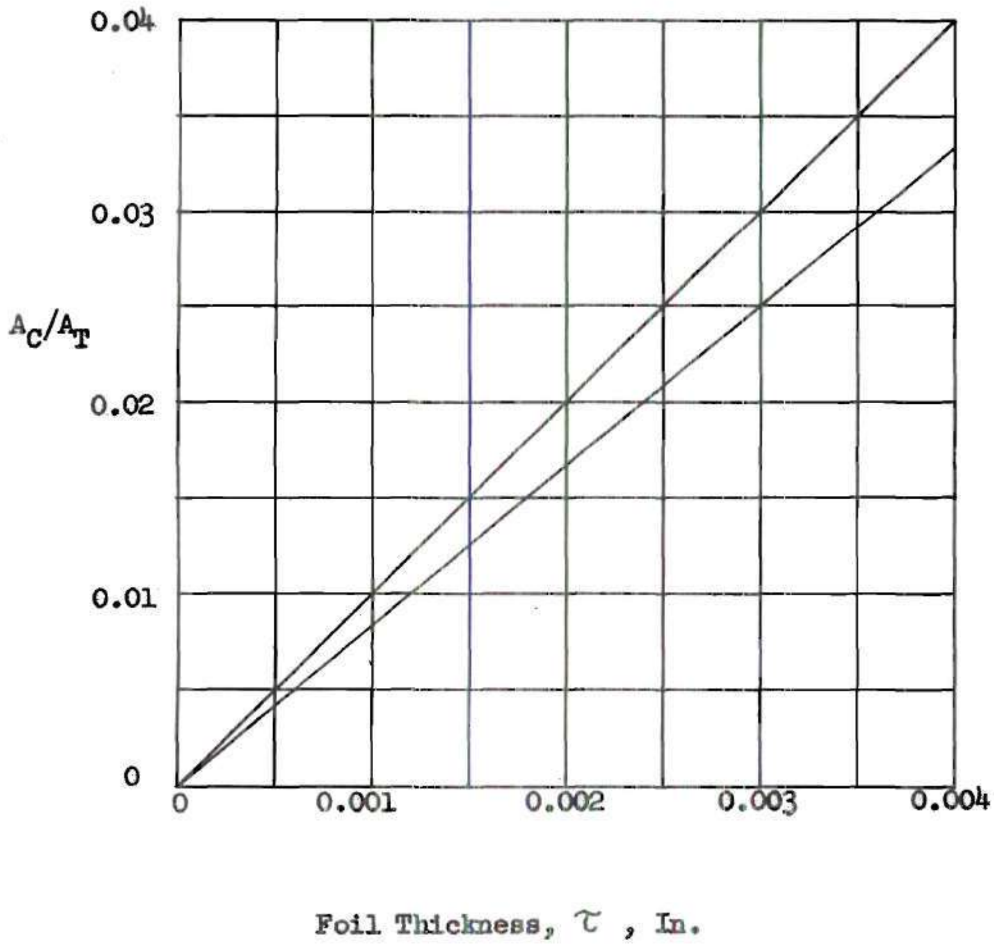


Figure 9. Variation of A_C/A_T With Core Foil Thickness

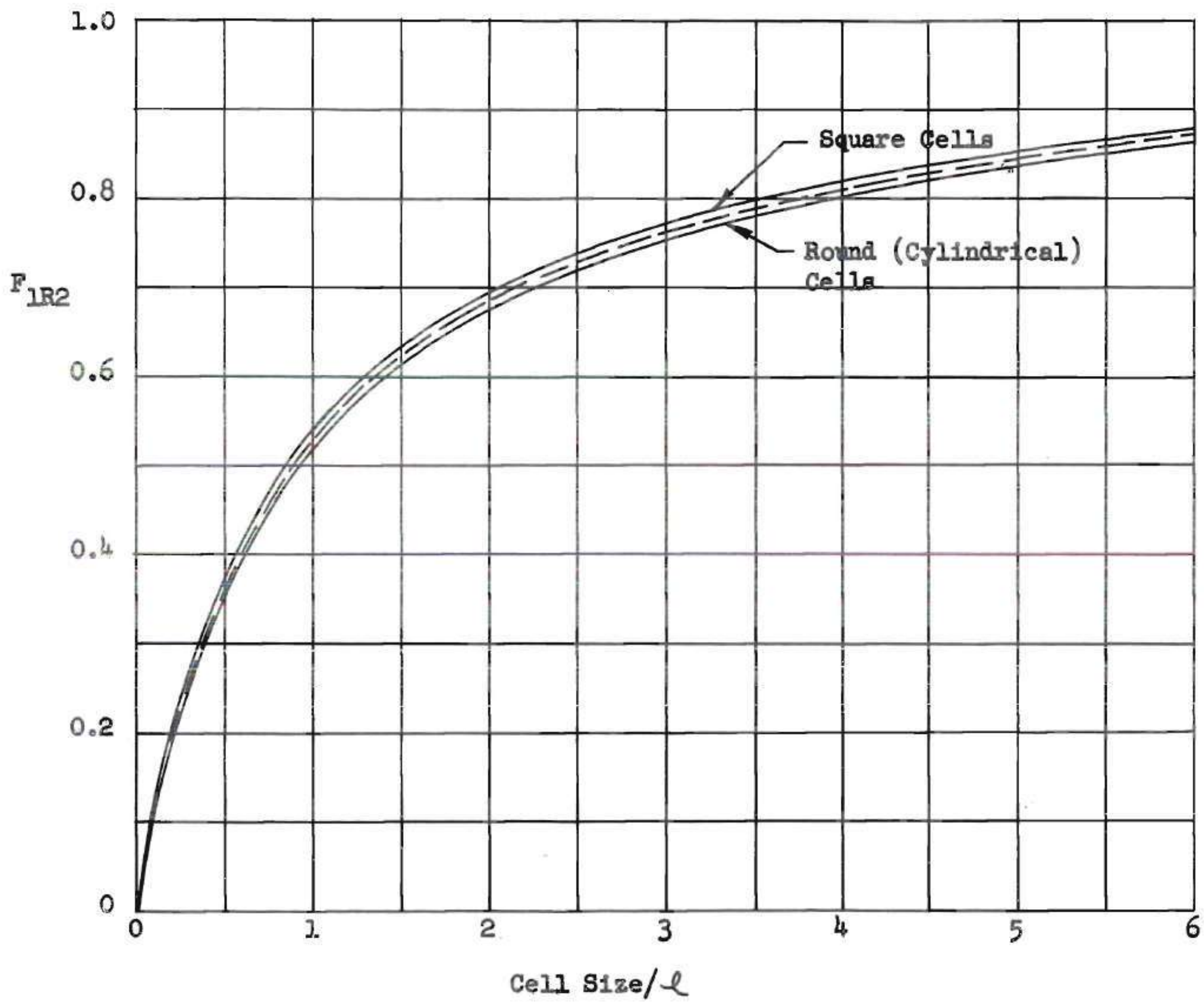


Figure 10. **Total Reradiation Factor Vs. Cell Size/ℓ**

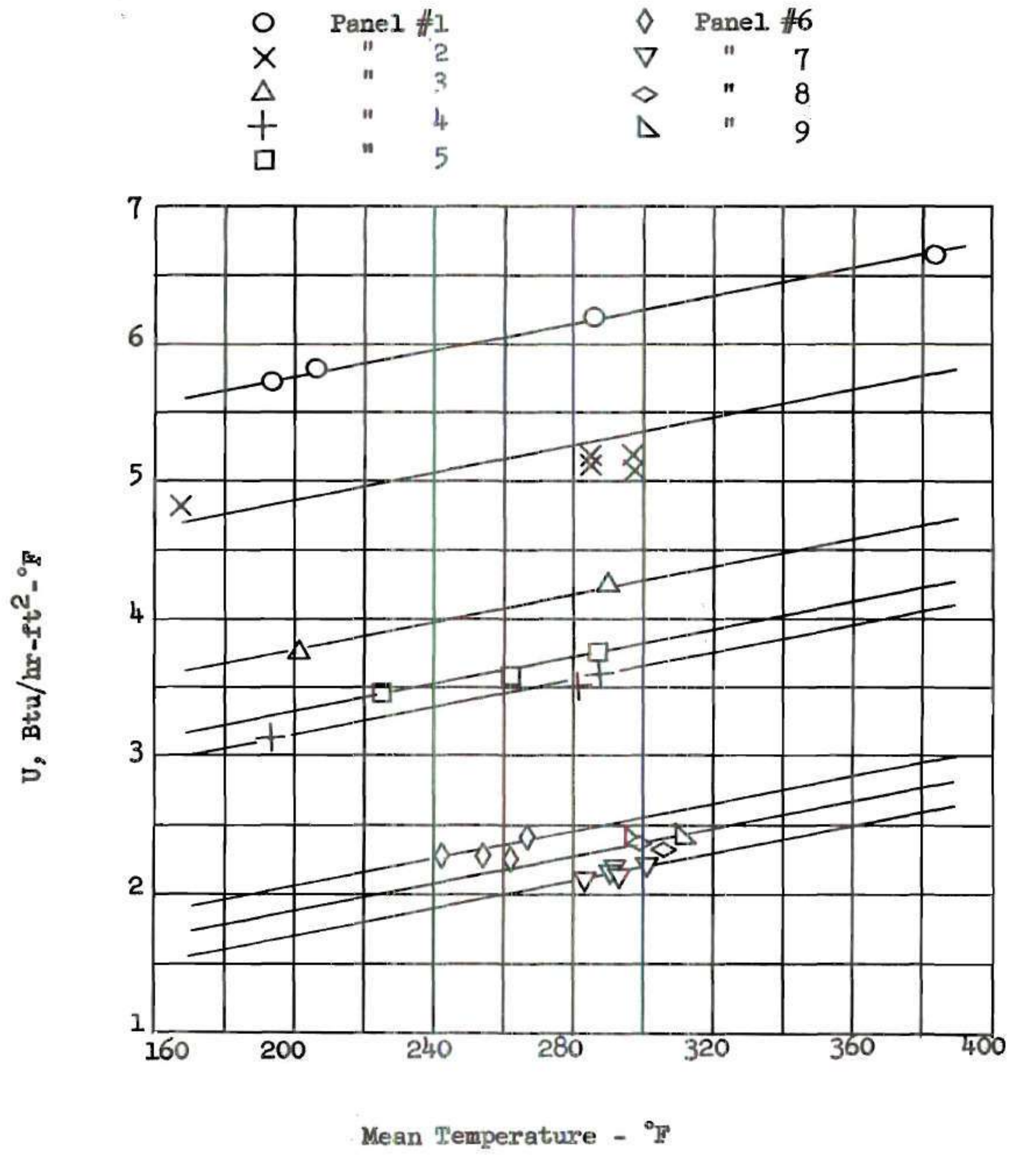


Figure 11. Summary of Experimental Data

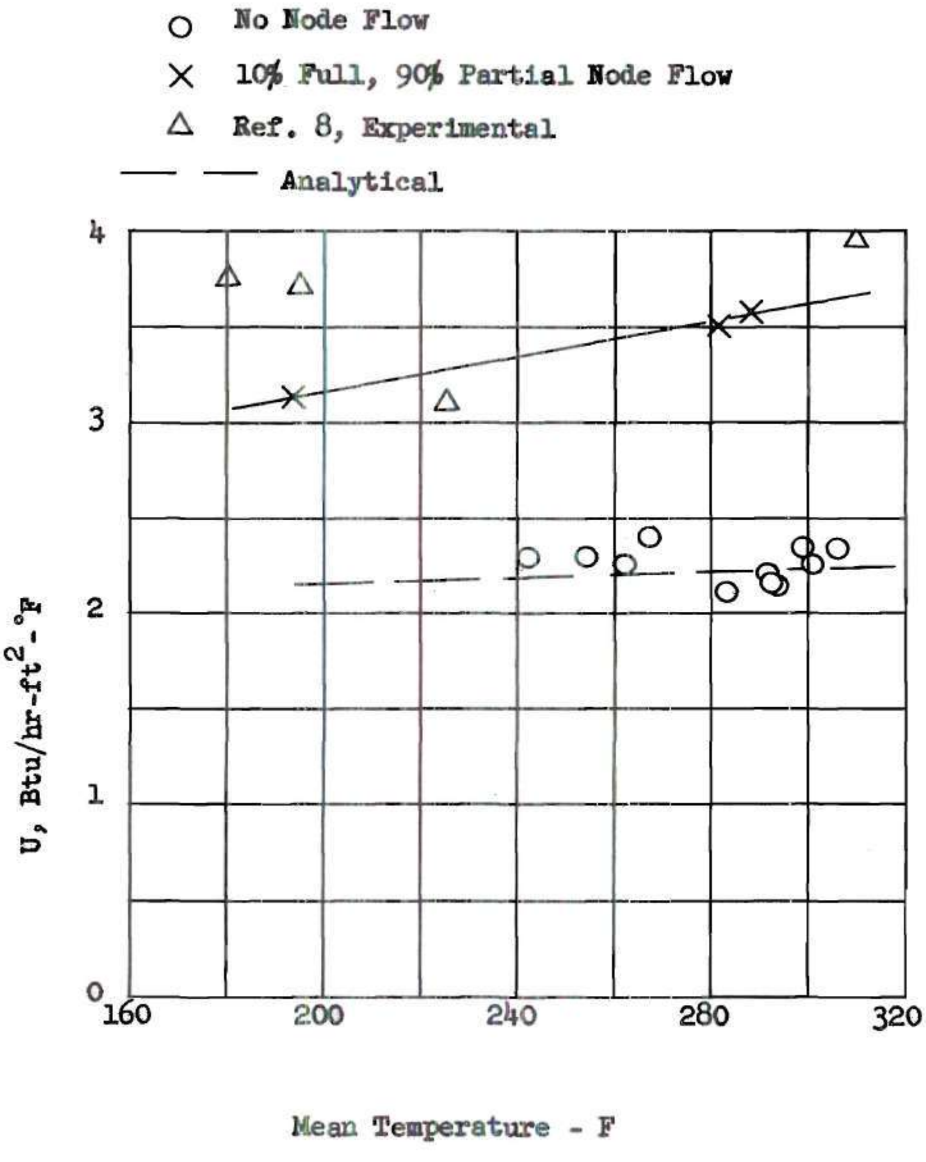


Figure 12. Comparison of Calculated and Experimental Data

APPENDIX A

SAMPLE CALCULATION FROM EXPERIMENTAL DATA

Hotside Temperature = 314 °F (Average of T/C's 1, 2, 3, and 4)

Coldside Temperature = 251 °F (Average of T/C's 10, 13, and 14)

Guard Temperature = 315 °F (Average of T/C's 5, 6, 7, and 8)

Volts = 9.75

Amperes = 1.08

<u>Total Heat In (Uncorrected)</u> = Volt x Amps x 3.41

= 9.75 x 1.08 x 3.41

= 35.9 Btu/hr

<u>Heat Flow Corrections</u>

1) Heat Flow Along Face Sheet

$$q_{GM} = \frac{k_F A_M \Delta T'}{d}$$

where k_F = Thermal Conductivity of Face Sheet Material

A_M = Area through which this heat is flowing = (face sheet thickness) x (perimeter of metered area)

$\Delta T'$ = Temperature Difference between Guard Area and Metered Area (Hot Side)

d = Distance from Guard Thermocouples to Edge of Metered Area = 1 Inch

For this example,

k_F = 9.80 Btu/hr-ft-°F

$$A_M = \frac{0.040 \times 25.5}{144} = 0.0071 \text{ ft}^2$$

$$d = 1 \text{ inch} = 0.0833 \text{ ft}$$

$$\Delta T' = 1 \text{ °F}$$

$$q_{GM} = \frac{9.80 \times 0.0071 \times 1}{0.0833} = +0.8 \text{ Btu/hr (GAIN)}$$

2) Heat Flow through Insulation of Hot Box

This portion is comprised of two factors, i.e., flow through the bottom and through the sides of the box.

The heat loss (or gain) through the bottom may be represented by

$$k_i \times \frac{49}{144} (T_{DE} - T_{AB})$$

where

$49/144$ = effective area through which this heat flows, ft^2

For this example, the heat flow through the bottom is

$$0.22 \times \frac{49}{144} (482 - 469) = +1.0 \text{ Btu/hr (GAIN)}$$

The heat loss (or gain) through the sides of the box may be represented by

$$k_i \times \frac{36}{144} (T_F - T_C)$$

where

$36/144$ = effective area of heat flow, ft^2

For this example, heat flow through the sides of the hot box is

$$0.22 \times \frac{36}{144}\,(413-418) = -0.3 \text{ Btu/hr (LOSS)}$$

Application of these corrections to the uncorrected value of total heat in gives

$$35.9 + 0.8 + 1.0 + (-0.3) = 37.4 \text{ Btu/hr}$$

Total overall coefficient of heat transmission is represented by

$$U = \frac{q_{corr}}{A \times \Delta T}$$

where A = effective area of test panel = 0.282 ft^2 thus,

$$U = \frac{37.4}{0.282 \times 63} = 2.11 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

APPENDIX B

SAMPLE CALCULATION FROM ANALYTICAL INVESTIGATION

The overall coefficient of heat transmission may be expressed as

$$U = U_C + U_G + U_R$$

The heat paths represented by the terms on the right hand side of the above equation are assumed to be independent of one another and will be treated as such in this investigation.

<u>Transmission by Conduction of Core Material</u>

Assumptions:

$T = 300\ ^\circ F$

Cell Size = 1/4" - 0.0015"

$U_C = \frac{k_C}{\ell} \frac{A_C}{A_T}$

$k_C = 9.73$ Btu/hr-ft-°F (page 33)

$\ell = 1$ in. = 0.0833 ft

$A_C/A_T = 0.0125$ (page 34)

$U_C = \frac{9.73}{0.0833} (0.0125) = 1.46$ Btu/hr-ft^2-°F

<u>Transmission by Conduction and Convection of Gas</u>

Assumptions:

Gas within cells is air at 1 atmosphere

$T = 300\ ^\circ F$

$\Delta T = 200\ °F$

Cell Size = 1/4" - 0.0015"

$$U_G = \frac{k_G}{\ell}\frac{k'_G}{k_G}\left(1 - \frac{A_C}{A_T}\right)$$

$k_G = 0.0204$ Btu/hr-ft-°F

$\ell = 1$ inch $= 0.0833$ ft

$$\frac{k'_G}{k_G} = 0.195(Gr_\ell)^{\frac{1}{4}}$$

where

$$Gr_\ell = \frac{\beta g}{\nu^2}\ell^3(T_1 - T_2)$$

and

$\beta = 0.001320/°R$

$g = 32.2\ ft/sec^2$

$\nu = 1.053\ ft^2/hr$ (Ref. 6)

$$\therefore,\quad \frac{k'_G}{k_G} = 2.96$$

Substituting,

$$U_G = \frac{0.0204}{0.0833}(2.96)(1 - 0.0125) = 0.72\ Btu/hr\text{-}ft^2\text{-}°F$$

Transmission by Radiation and Re-Radiations

Assumptions:

$T_1 = 400\ °F = 860\ °R$

$$T_2 = 200\ °F = 660\ °R$$

Cell Size = 1/4" - 0.0015"

$$U_R = \frac{F_{1R2}\sigma F_e(T_1{}^4 - T_2{}^4)}{(T_1 - T_2)} \frac{A_G}{A_T}$$

where

$$F_{1R2} = 0.23 \text{ (page 35)}$$

$$\sigma = 0.173 \times 10^{-8} \text{ Btu/hr-ft}^2\text{-°R}^4$$

$$F_e = \varepsilon_1\ \varepsilon_2 = 0.010 \text{ (Ref. 1, 7)}$$

$$A_G/A_T = 0.9875$$

$$U_R = \frac{(0.23)(0.173)(0.010)\left[\left(\frac{860}{100}\right)^4 - \left(\frac{660}{100}\right)^4\right](0.9875)}{200}$$

$$= 0.01 \text{ Btu/hr-ft}^2\text{-°F}$$

Overall Coefficient of Heat Transmission

As previously stated,

$$U = U_C + U_G + U_R$$

Therefore, $U = 1.46 + 0.72 + 0.01 = 2.19$ Btu/hr-ft^2-°F

APPENDIX C

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